III-V Semiconductor Unipolar Barrier Infrared Detectors for Earth Science Applications

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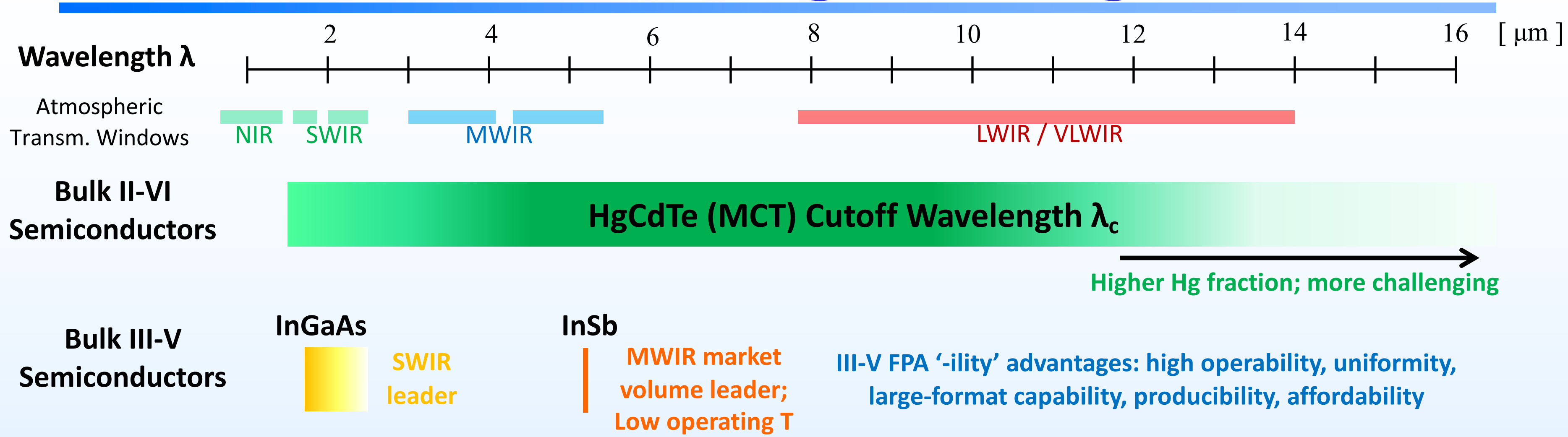
Outline

- Background
- Recent advances in III-V infrared detectors
  - Absorber material – type-II superlattice
  - Unipolar barrier device architecture
- Type-II superlattice unipolar barrier infrared detectors
- Summary

Background

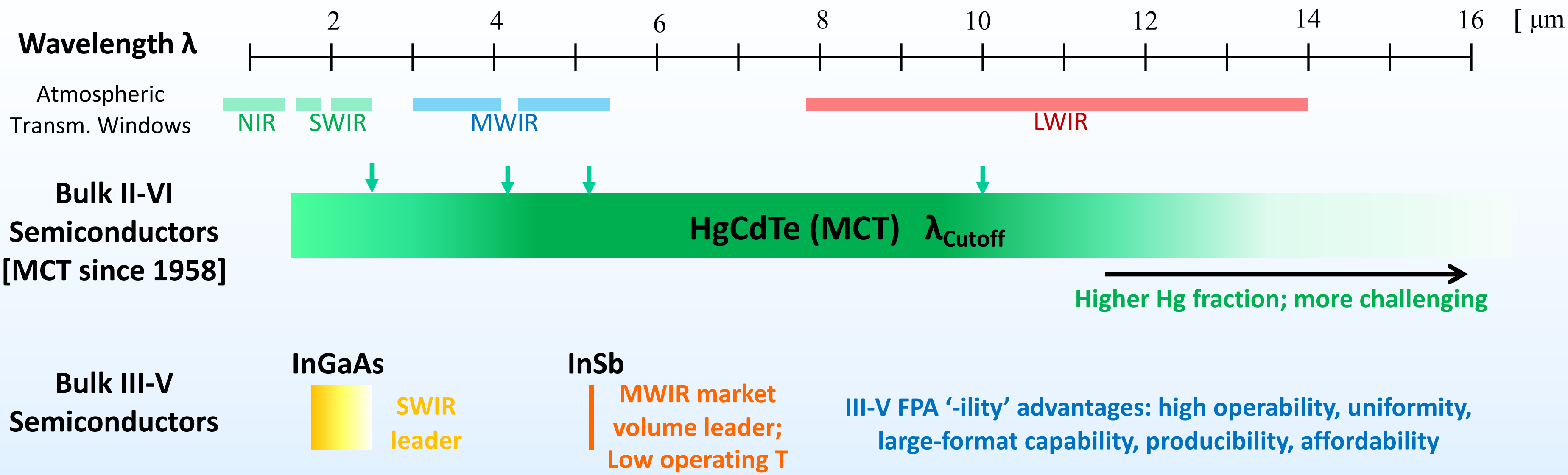
Traditional Bulk II-VI semiconductor (HgCdTe)
and
III-V semiconductor IR detectors

Traditional Bulk Infrared Material Cutoff Wavelength Coverage

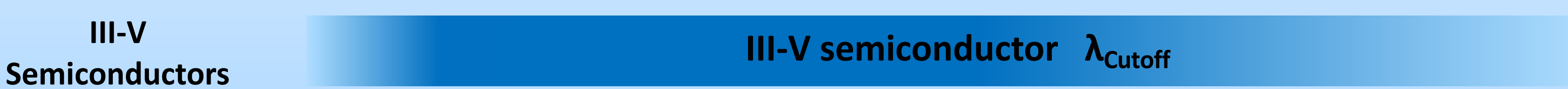


- **HgCdTe** alloy (**MCT**) is the most successful infrared material to date
  - High-performance detector. Varying alloy composition provides continuously adjustable cutoff wavelength coverage, ranging from NIR to VLWIR
  - Soft and brittle. Requires expert handling in growth, fabrication, storage. Costly.
  - Weak Hg-Te bond. Longer λ_{cutoff}, higher Hg fraction, progressively more challenging
- FPAs based on (near) lattice-matched bulk **III-V** semiconductor photodiodes are highly successful, but only in a few cases where suitable substrates are available.
  - SWIR **InGaAs** performs at near theoretical limit
    - Single color, limited cutoff wavelength adjustability
  - **InSb** dominates MWIR market, despite lower operating temperature than MCT
    - Fixed cutoff wavelength, single color
  - Lacking the continuous cutoff wavelength adjustability of MCT

III-V Infrared Detector with adjustable λ_{Cutoff} ?



Can we achieve continuously adjustable λ_{Cutoff} , covering SWIR to VLWIR, using III-V semiconductors ?



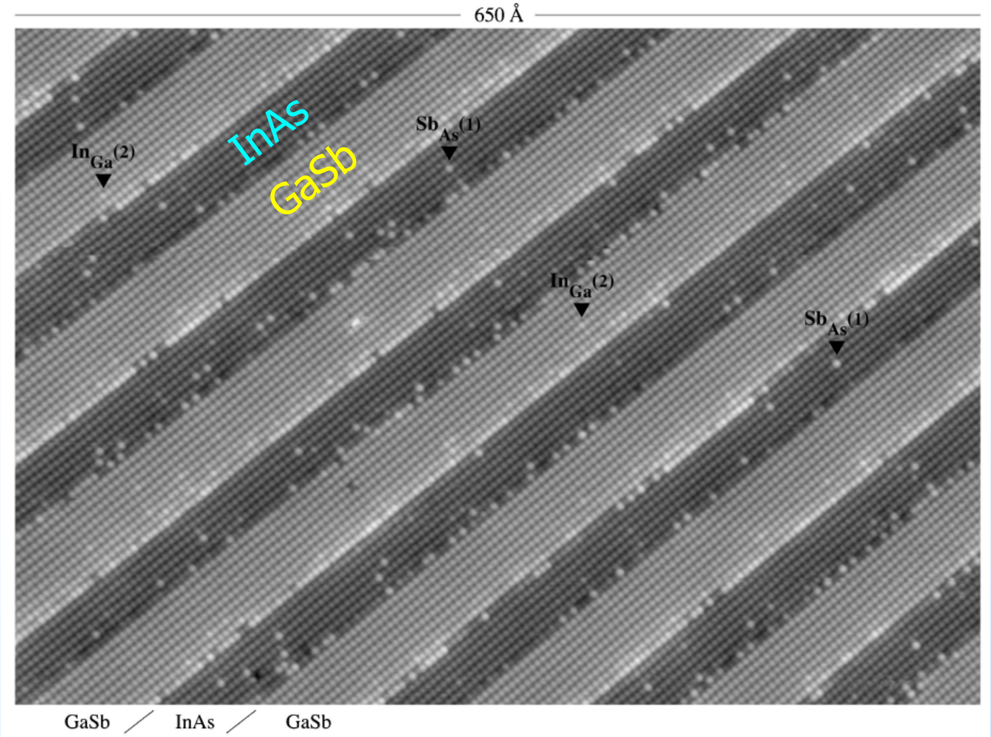
III-V Robustness + MCT Versatility ??

Recent advances in III-V infrared detectors

Absorber material – Type-II superlattice

Unipolar barrier device architecture

Semiconductor Superlattices

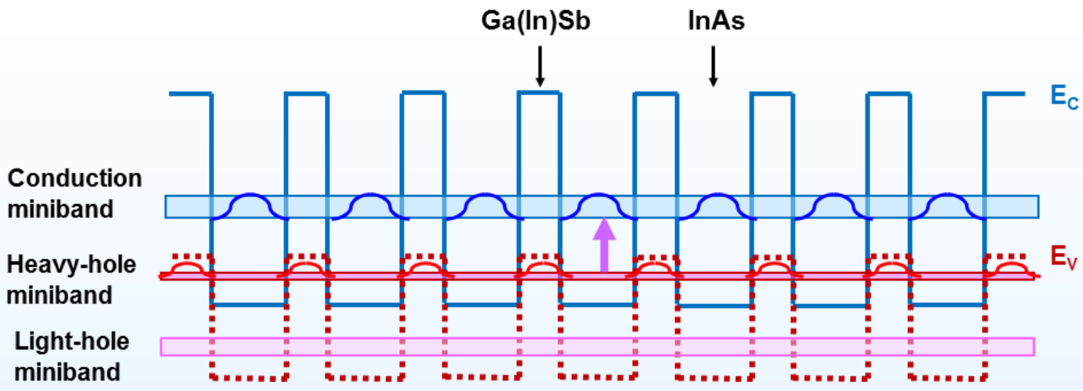


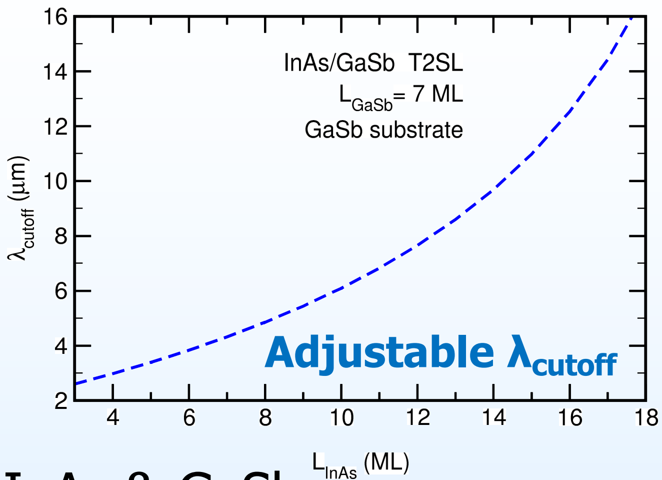
Cross-sectional scanning tunneling microscope (XSTM) image, InAs/GaSb SL. M. Weimer Group, Texas A & M. [*J. Vac. Sci. Technol*. B **23**□**3**□, 1-5 (2005).]

- Artificial crystalline material grown atomic layer by layer
- Periodic structure, usually made from two alternating semiconductors
  - E.g., InAs/GaSb
- "Band structure engineered material": Electric, transport, and optical properties can be adjusted by design

- Type-II superlattice (T2SL) of particular interest for infrared detectors
  - Energy band gap can be made smaller than the constituent semiconductors
  - Also: type-II strained-layer superlattice (T2SLS)
- Examples of infrared T2SL that can be grown on GaSb substrate
  - **InAs/GaSb**, InAs/GaInSb, **InAs/InAsSb**, InAs/InSb, InAsSb/InSb

Antimonide Type-II Superlattices: Features and Advantages



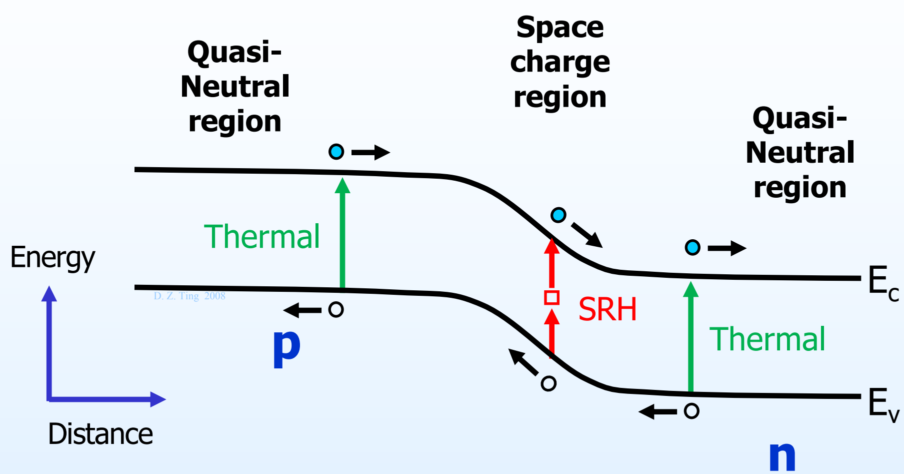


- Type-II broken-gap band alignment between InAs & GaSb
  - Electron wave functions localized in InAs; hole wave functions in GaSb layers (type-II)
  - GaSb E_v is higher than InAs E_c (Broken gap)
- Band gap can be made smaller than constituent bulk semiconductors
  - Suitable for IR detection
- Sufficiently large absorption coefficient to achieve ample QE
- Continuously adjustable band gap / λ_{cutoff} by varying layer widths
  - Covering SWIR, MWIR, LWIR, and VLWIR
- Dark current reduction in superlattice
  - **Can be engineered for Auger suppression**
  - **Less susceptible to tunneling**

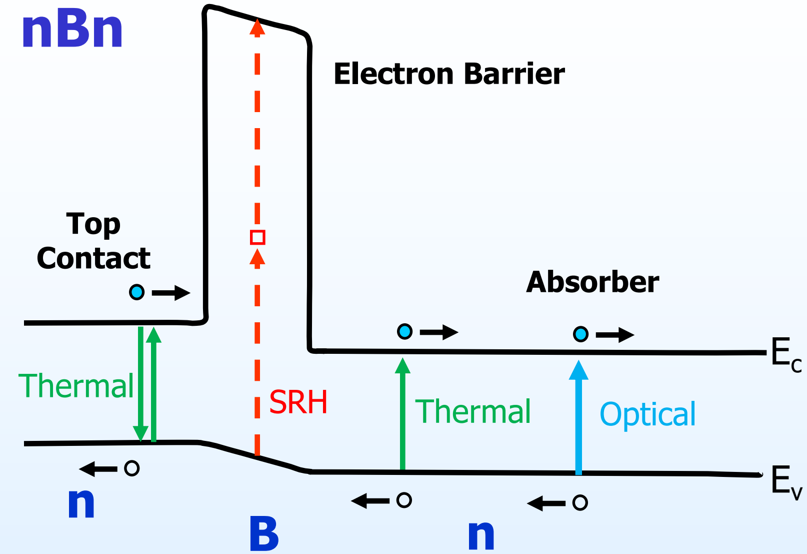
Review Book Chapter:
"Type-II Superlattice Infrared Detectors",
D. Z. Ting, A. Soibel, L. Höglund, J. Nguyen, C. J. Hill, A. Khoshakhlagh, and S. D. Gunapala, Semiconductors and Semimetals **84**, pp.1-57 (2011).

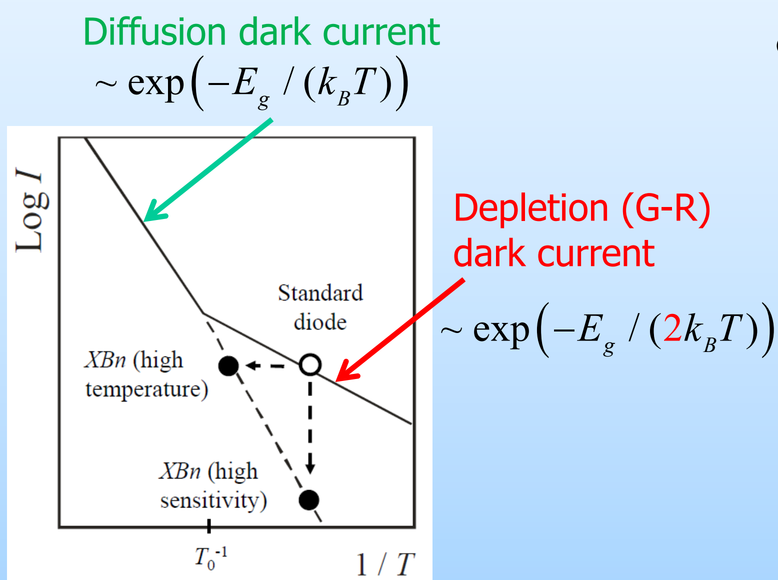
The nBn detector

p-n diode



nBn

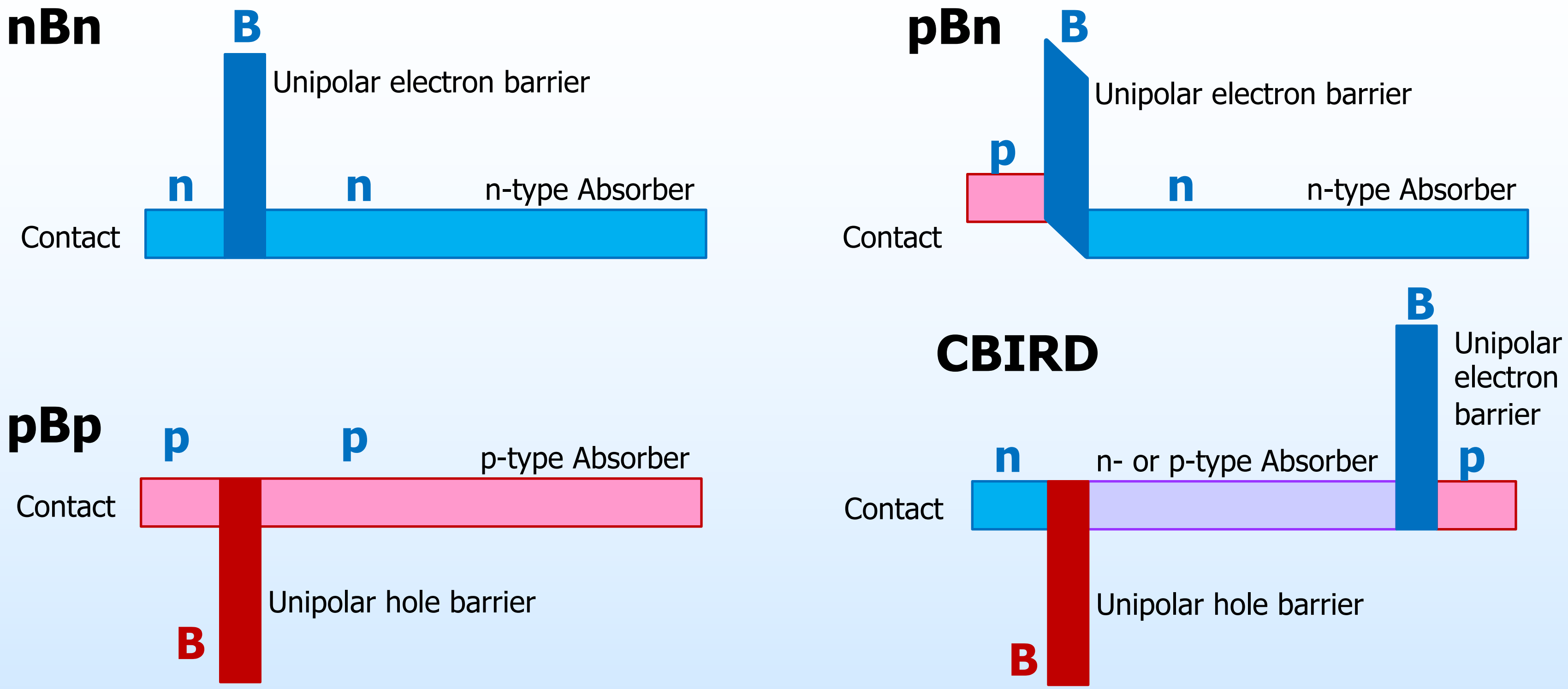




Klipstein, Proc. of SPIE Vol. 6940, 69402U, (2008)

- The nBn
  - Maimon & Wicks, *Appl Phys Lett* (2006)
    - 351 citations as of May 2019 (Web of Science)
  - Barrier blocks electrons but not holes
  - SRH processes are drastically reduced in wide-band-gap barrier region
  - Suppresses G-R dark current
  - Photocurrent flows un-impeded
  - Resulting in higher operating temperature / sensitivity
  - Also suppressed surface leakage current

Unipolar Barrier Device Architecture



- A variety of unipolar barrier architectures for single- and dual-band devices
- The **challenge** is in finding heterostructures with
  - Matching absorber and barrier conduction or valence band edges
  - Both absorber and barrier should be closely lattice-matched to the substrate
    - Barrier layers tend to be thin; lattice-matching requirement less stringent
- The antimonides (InAs, GaSb, AlSb and their alloys) provide an ideal material system for implementing unipolar barrier infrared detectors

Type-II superlattice (T2SL) unipolar barrier infrared detectors

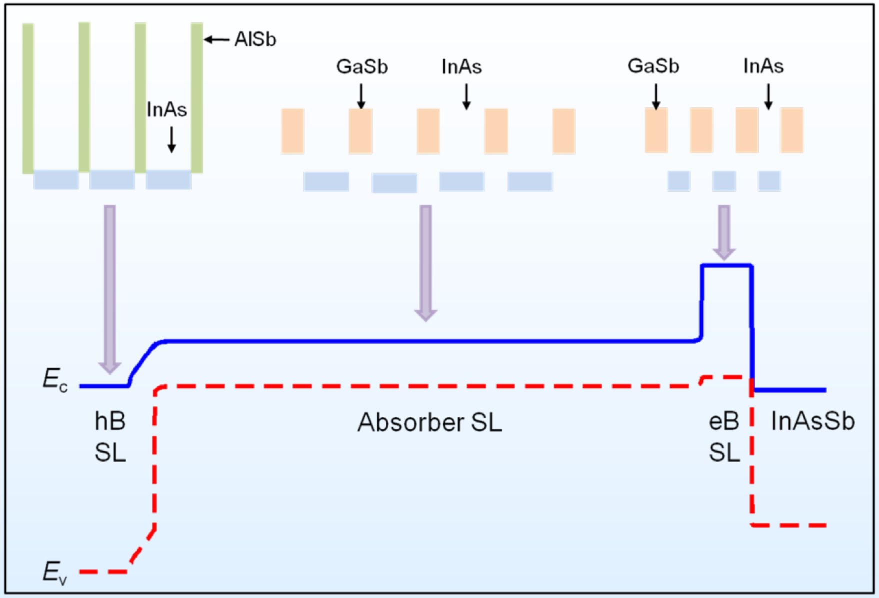
LWIR InAs/GaSb T2SL CBIRD

MWIR InAs/InAsSb T2SLS nBn

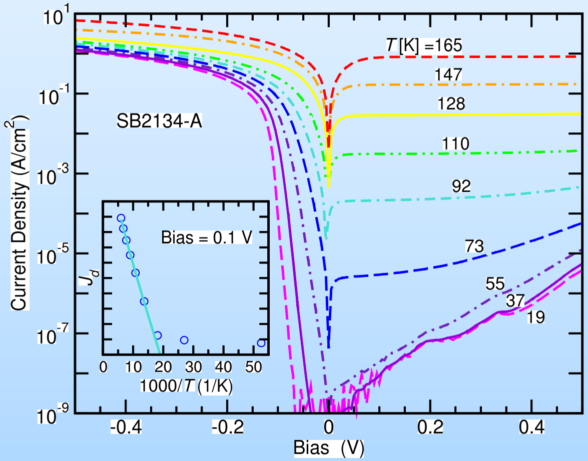
MWIR FPA for CubeSat Spectral Imaging

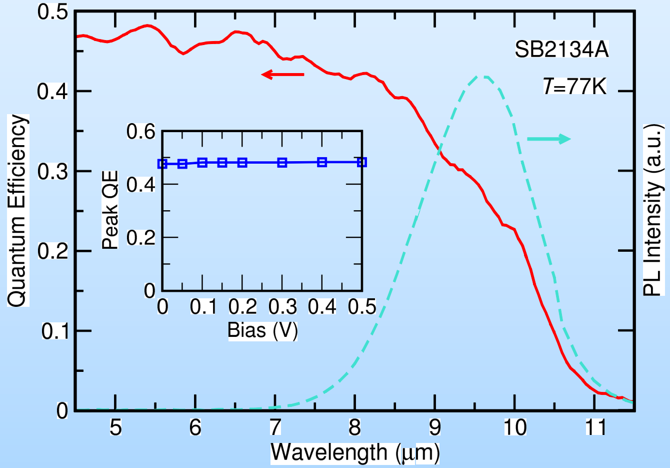
VLWIR FPA for SLI-T

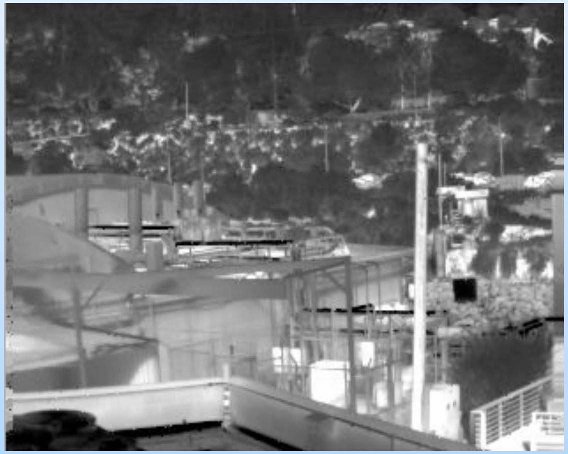
LWIR InAs/GaSb Type-II Superlattice Complementary Barrier Infrared Detector (CBIRD)



- Complementary Barrier Infrared Detector
  - p-type LWIR **type-II superlattice absorber**
  - **unipolar hole barrier** (hB)
  - **unipolar electron barrier** (eB)
- LWIR detector
  - 9.8 μm cutoff (50% peak QE)
  - QE=40% (λ=8.5 μm, no AR coating)
  - Zero-bias turn-on
  - J_d(0.1V, 77K) = 0.8x10^{-5} A/cm^2 (~4.2x Rule'07)
- FPA with high uniformity and operability



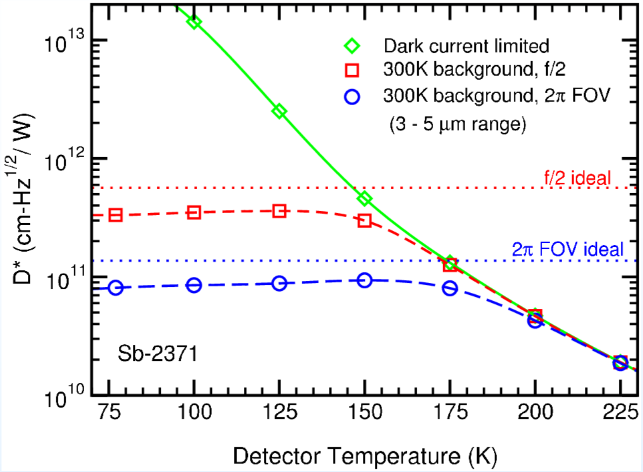


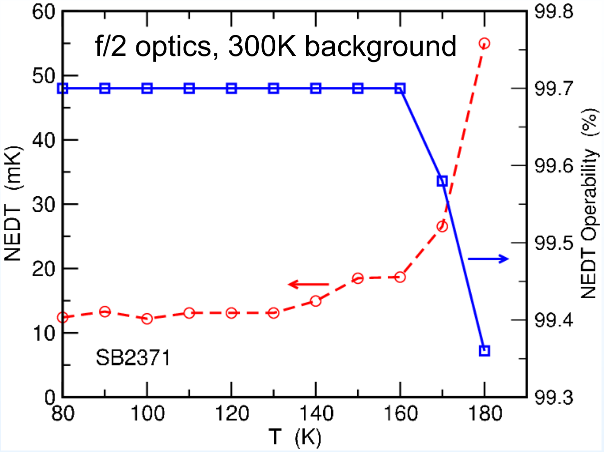


ISC 0903 DI, 320x256, 30 μm pitch
NEΔT – 18.6 mK (f/2, 300K)
[Rafol et al., *JQE* **48**, 878 (2012)]

Ting et al., *Appl. Phys. Lett.* **95**, 023508 (2009) (236 citations as of May 2019); *Appl. Phys. Lett.* **102**, 121109 (2013); U. S. Patent No. 8,368,051 (2013)

MWIR InAs/InAsSb Type-II Strained-Layer Superlattice High Operating Temperature Barrier IR Detector (HOT-BIRD)

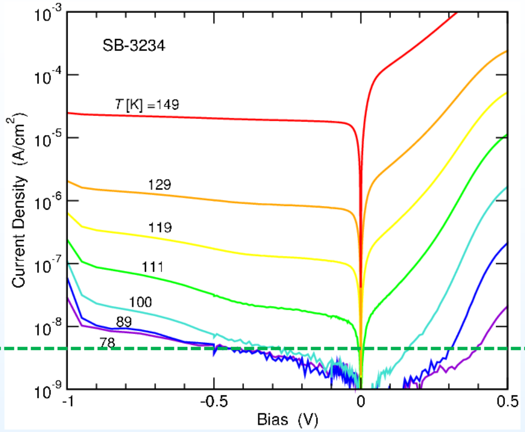


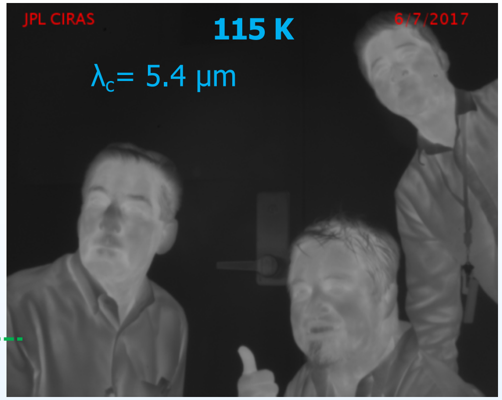


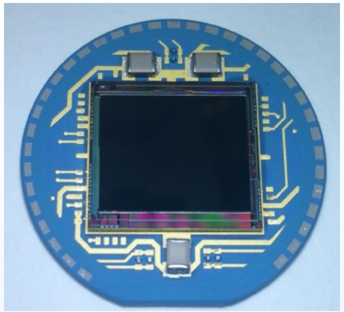
- MWIR InAs/InAsSb T2SLS nBn detector and FPA
  - Cutoff wavelength: 5.37 μm (160 K); QE(4.3 μm, 150K)=52% (No A/R coating)
  - J_{dark}(-0.2V, 157K)=9.6×10^{-5} A/cm^2 (~4.5X Rule'07)
  - D*=3 ×10^{-11} cm-Hz½/W at 150K operating temperature (f/2 optics, 300 K background)
  - FPA: 160K NEDT=18.7 mK, operability =99.7%; 170K NEDT=26.6 mK, operability =99.6%
- Designed for same λ_{cutoff} , operates at much higher temperature than InSb
  - Planar InSb (ion implant) ~ 80K. MBE epi InSb ~ 95-100K (can image up to 110-120K)
  - Reduced cryo-cooler Size, Weight, and Power - SWaP advantages
  - Retains benefits of III-V semiconductor robustness ("ility" advantages)
  - InSb is a major incumbent technology
    - InSb FPAs account for >50% of all photodetector FPAs sold in 2018 (G. Fulop, Maxtech International, Inc.)

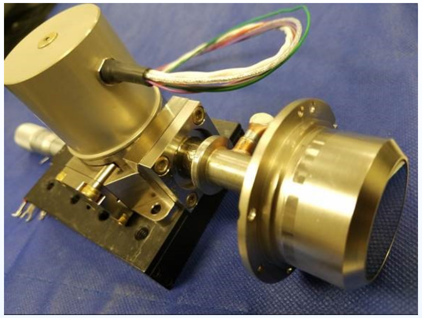
Ting et al. *Appl. Phys. Lett.* 113, 021101 (2018); *IEEE Photonics J.* **10**(6), 6804106 (2018); U. S. Patent No. 8,217,480 (2012)

MWIR T2SL Detectors & FPAs for Earth Science Imaging Spectrometer Applications









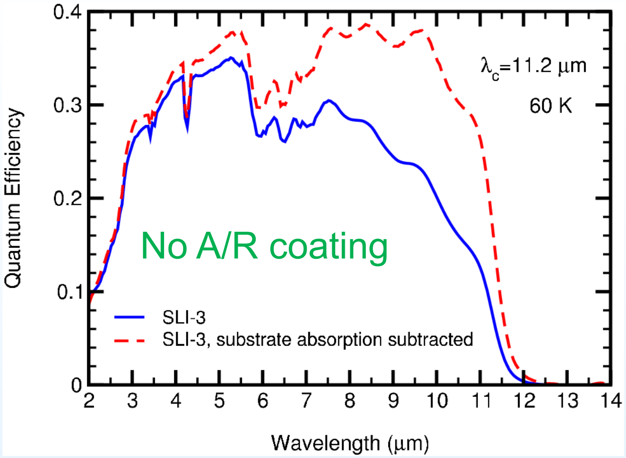
Mounted focal plane array (FPA) and integrated dewar cooler assembly (IDCA).

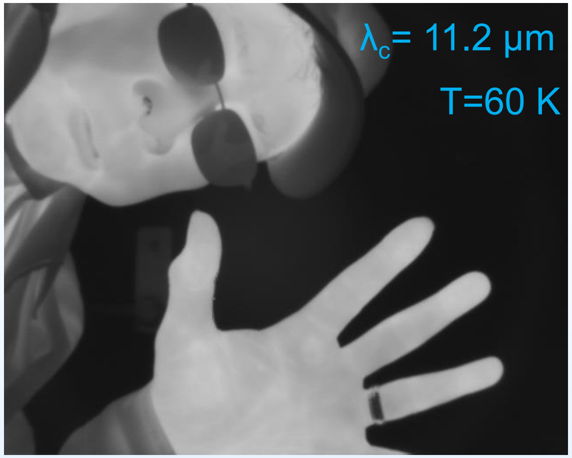
- NASA CubeSat Infrared Atmospheric Sounder (CIRAS): Spectral imaging (intermediate background) requires good low-T dark current characteristics
- Detectors specifically designed to meet the requirement for this application
  - λ_{cutoff} ~ 5.4 µm at 120K. J_{dark}(-0.2V,111K)=1.8x10^{-8} A/cm^2 (~3x Rule'07).
  - Nearly diffusion-limited dark current to below 110K
- FPA
  - Mean J_{dark}(115K)=1.6x10^{-7} A/cm^2 ; mean QE ~55% in 3 – 5 µm band at 120K
  - Mean NEDT (115K) = 20.1 mK (σ= 3mK), 300K background, F/7.8
  - NEDT operability: 99.99%

Ting et al., *SPIE Proc*. **10624**, 1062410 (2018).

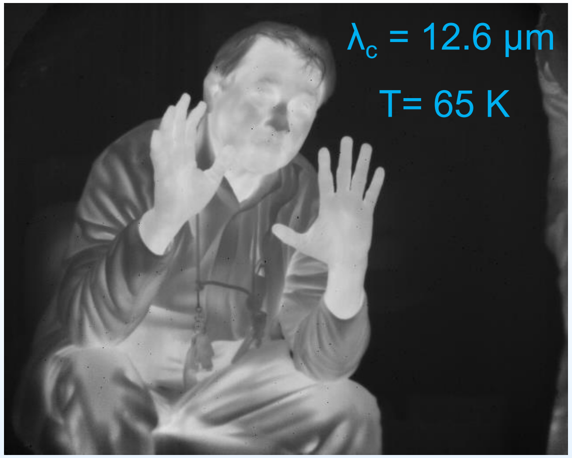
CIRAS: Pagano et al., *SPIE Proc*. **10402**, 1040209 (2017); *SPIE Proc*. **10769**, 1076906 (2018)

VLWIR T2SL Detectors & FPAs for SLI-T





99.7% operability (17SLL03)



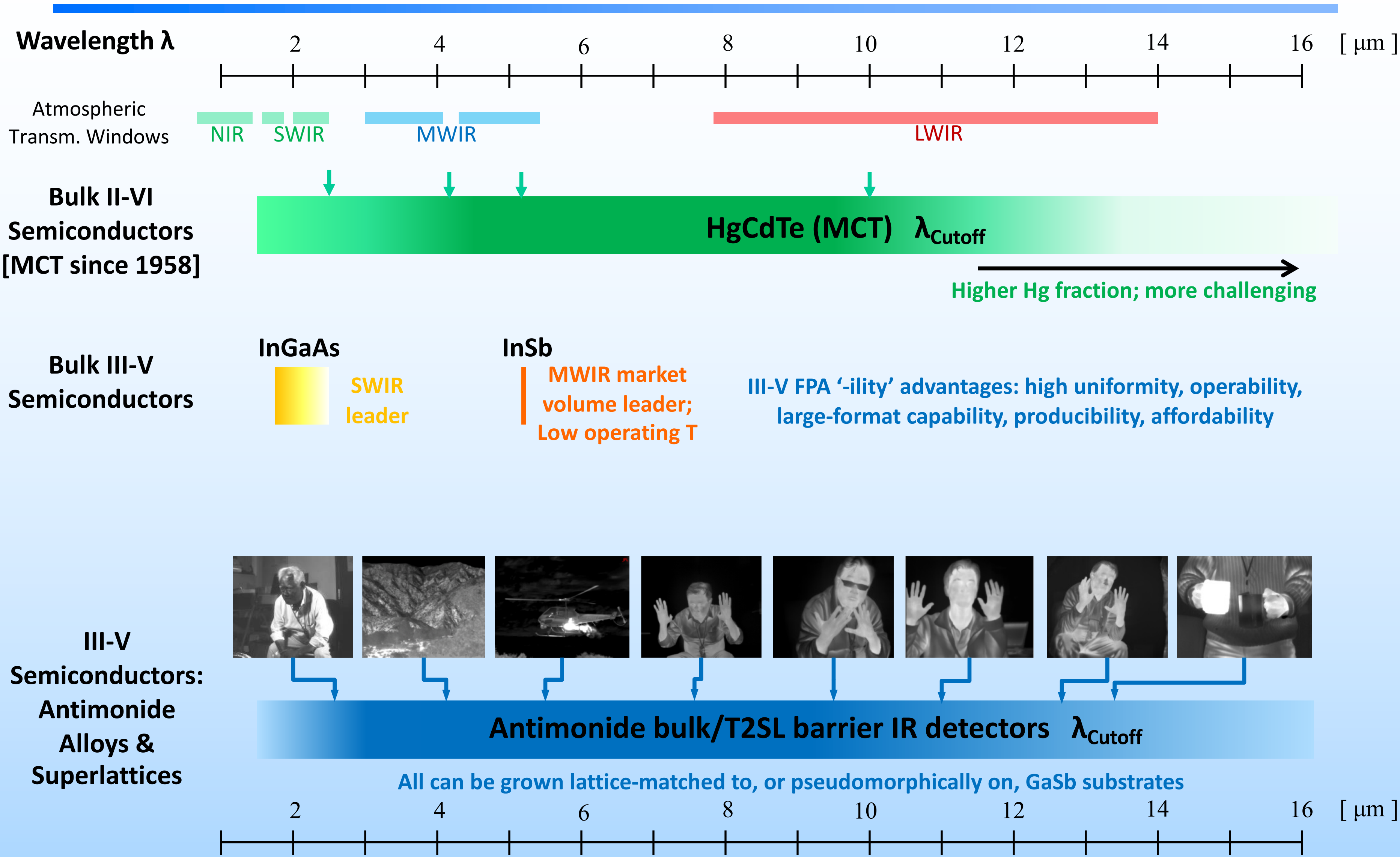
99.98% operability (18SLL03)

- Developing T2SL-based LWIR detectors for NASA Sustainable Land Imaging Technology (SLI-T) Program
- Unipolar barrier infrared detector architecture, T2SL absorber
  - High quality λ_{cutoff} ~ 11.2 μm T2SL absorber material
  - 240 ns minority carrier lifetime
  - J_{dark}(60K)~10^{-5} A/cm^2 ; QE ~ 37% without A/R coating.
  - Very good FPA operability
- λ_{cutoff} ~ 12.6 μm detectors/FPAs also demonstrated. Optimization ongoing.
- Collaborating with industry to demonstrate compact camera core

Ting et al., *SPIE Proc.* **10624**, 1062410 (2018).

Summary

Antimonide Unipolar Barrier Infrared Detectors



Summary

- Significant advances in III-V semiconductor infrared detector development in the past decade
  - Infrared absorber material – e.g. type-II superlattices
  - Detector architecture – unipolar barriers
  - The antimonides provides an excellent platform for implementing III-V unipolar barrier infrared detectors and focal plane arrays

- MWIR InAs/InAsSb T2SL FPAs operate at significantly higher temperature than market leading InSb FPAs
- Low dark current MWIR T2SL FPAs suitable for spectral imaging applications

- VLWIR T2SL FPAs being developed for land imaging applications under SLI-T